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PROGRAM TO RESEARCH LASER-DRIVEN
THERMIONIC ELECTRON SOURCES
FOR FREE ELECTRON LASERS

(Contract N00014-83-C-0333)

Final Report

TE Thermo Electron

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ABSTRACT

This is the Final Report on the research and development of high brightness pulse laser-driven thermionic electron sources.

Enhanced coupling of electron beam energies to radiative fields in accelerator-driven free-electron lasers requires injector cathodes of higher brightness than is possible with conventional dispenser cathodes or plasma-forming field emitters. Cesiated refractory surfaces and dispenser cathodes which are pulse laser heated may offer such an increase in brightness, by the emissison of monoenergetic beams of electrons at high current densities. These studies were designed to investigate the emission characteristics of both of these types of thermionic cathodes. Experiments were performed with 50-ns pulses of 1.06-μm laser radiation on 0.75-cm^2 or 1-cm^2 surfaces. Measurements indicated that thermionic space-charge-limited currents are generated which, for the cesiated surfaces, are due to thermal nonequilibrium processes. The rapidly rising (<10 ns) current pulses were often observed to turn into plasma dominated emission.

Dispenser cathodes are conventionally operated in a continuous mode at maximum current densities of 10 to 20 A/cm^2. Even higher levels are possible if the dispenser cathode is operated in a pulsed mode with temporal lengths tailored to the accelerators' characteristics. Pulse widths of 20 to 50 ns, required by LLNL's Advanced Test Accelerator (ATA), can

be achieved by rapidly heating the dispenser surface with
existing Q-switched lasers. Thermionic currents of 75 A and
current densities of 200 A/cm^2 are reported herein from
such single-shot experiments. The irradiating source was a
Q-switched Nd:glass laser operating at its fundamental
frequency. Corresponding observations of the fluorescence
from the diode, at a wavelength of 600nm, indicated an
initial region, nominally 50 ns wide, of non-fluorescing
purely thermionic flow. Additional evidence for the delay in
plasma formation was obtained from experiments using a triode
with the third electrode (Faraday cup) at the same potential
as the anode.

INTRODUCTION

Requirements for pulsed, temporally well-defined, high-brightness electron sources are increasing. A class of devices especially in need of such emitters are free-electron (FELS). Conventional plasma and dispenser cathodes are limited in the brightness they can achieve. However, laser-driven photoemissive and thermionic cathodes are good candidate sources. Such photocathodes have been developed[1,2] and tested[3] in a 1 MeV injector and shown with visible laser irradiation to generate current densities of hundreds of amperes per square centimeter in pulse lengths of tens of picoseconds, and at high repetition rates. The brightness of the beam approach 10^{11} A/m^2-rad^2, an order of magnitude better than that obtained with other cathodes. By contrast, thermionic emitters are still in an early developmental stage, but show great promise as generators of equally high current densities in longer (tens of nanoseconds) pulses, and operable in less stringent environmental conditions. Moreover, the necessary irradiating lasers driving such thermionic cathodes emit in the more available IR region (e.g., fundamental radiation from Nd:YAG, glass, or CO_2). Furthermore, the electron emission in thermionic processes is exponentially dependent on the incident radiation intensity, which is superior in energy conversion efficiency to the linearly dependent photoemission. The thermionic sources are well suited to FELs driven by induction linacs. For example, LLNL's ATA requires pulse

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lengths in the range of 30 to 50 ns, which correspond to the Q-switched laser pulse widths used in our experiments.

Thermionic emission from both laser-driven cesiated- and dispenser-cathodes have been investigated[4]. Rapid heating of the emitting surfaces by the laser pulse appears to generate during the early part of the pulse, an electron flow dominated by thermionic processes. A larger current, subsequently generated, is attributed to the formation of a plasma, which becomes more pronounced as the capacitance furnishing the charge in the diode is increased. Reducing the capacitance to picofarads has only a modest effect on the thermionic flow, but seems to severely limit the plasma formation by reducing the available charge.

Although laser-driven cesiated cathodes appear superior to conventional cathodes in brightness, and have relatively long pulse lengths, they must be operated in a reasonably clean environment. Oxygen, water vapor and organic species will rapidly poison the surface. Furthermore, the high volatility of cesium from a heated cathode surface requires that this element be continually replenished from a nearby source. With proper design, a cathode enclosure can be provided which effectively isolates a region adjacent to the emitting surface from the rest of the accelerator. Differential pumping and cavity cooling can be used to keep this region clean. Such isolation is impractical for larger emitters, but is adaptable to cathodes emitting small area beams of a few square centimeters or less.

The concept of pulse heating conventional dispenser cathodes with ir lasers in this manner is attractive, because it will allow high currents to be generated with standard devices operating in conventional accelerator vacuums of 10^{-6} torr. Commercial B-type cathodes composed of barium, calcium, and aluminum oxides, can emit current densities of 100 A/cm^2 when pulse heated to about 1625 K. Excessive evaporation of barium from the dispenser surface will be minimal, on a time-averaged basis, if the accelerator is operated in a low-duty mode. For example, 50-ns pulses at a repetition rate of 2 KHz result in reducing the average barium evaporation rate to 10^{-3} of that when such an emitter is continuously operated at its customary temperature of 1400 K. Chemical activation and proper diffusion of the barium to the surface is accomplished between pulses by a "keep alive" continuous heating of the cathode to a temperature below that which would generate significant electron emission.

The objectives of the study were to perform experimental investigations of the phenomenon of thermionically emitting electrons from either a cesiated tungsten surface or a dispenser cathode, frontally illuminated and rapidly heated by a pulsed laser. The emphasis was on gaining some basic understanding of the physics of the surface interactions and ensuing plasma processes in order to determine what limitations may be imposed on these new sources of potentially very bright electrons beams. In line with these objectives, measurements were made of the thermionic emission of electrons from a B-type

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dispenser cathode in a diode configuration, and from a bare tungsten substrate in a triode geometry, both frontally heated by a 50-ns (FWHM) pulse from a Nd:glass laser radiating at its fundamental wavelength. Observations were made of the temporally resolved emitted current and fluorescence from the diode, and of the currents to the anode and Faraday cup in the triode. By varying the charge supplying capacitators, the characteristics of the electron emission processes could be deduced from these measurements.

EXPERIMENTAL STUDIES

Both cesium-coated and B-type dispenser cathodes were frontally illuminated by a Q-switched Nd:glass laser beam emitting at 1.06 μm with a pulse width (FHWM) of 50 ns. Tests on these two types of thermionic cathodes were performed sequentially and are described separately in the following sections:

CESIUM-COATED CATHODES

The experimental arrangement for investigating thermionic emission for cesium coated surfaces is shown in Figure 1. A circular tungsten cathode, 1 cm^2 in area, is positioned 1 cm from a cylindrical anode in a vacuum chamber pumped to below 10^{-7} torr. A cesium reservoir (not shown) is connected to this chamber. The reservoir consists of a small tube containing a glass cesium ampule. After initial installation, the ampule is mechanically cracked by pinching the tube, and heater tapes are used to drive the cesium into the experimental chamber. With this enclosure at room temperature, the cesium vapor pressure in the diode is 10^{-6} torr. At such a pressure, monolayer coverage of the tungsten cathode occurs in about one second. Fractional (0.2 to 0.3) monolayer coverage will provide a minimum work function for the cesium/tungsten combination of approximately 1.6 eV.

With the Nd:glass laser beam pulse heating the cathode and the charge supplied by 0.5 μF capacitor, a series of temporally resolved traces was obtained of emitted current, at
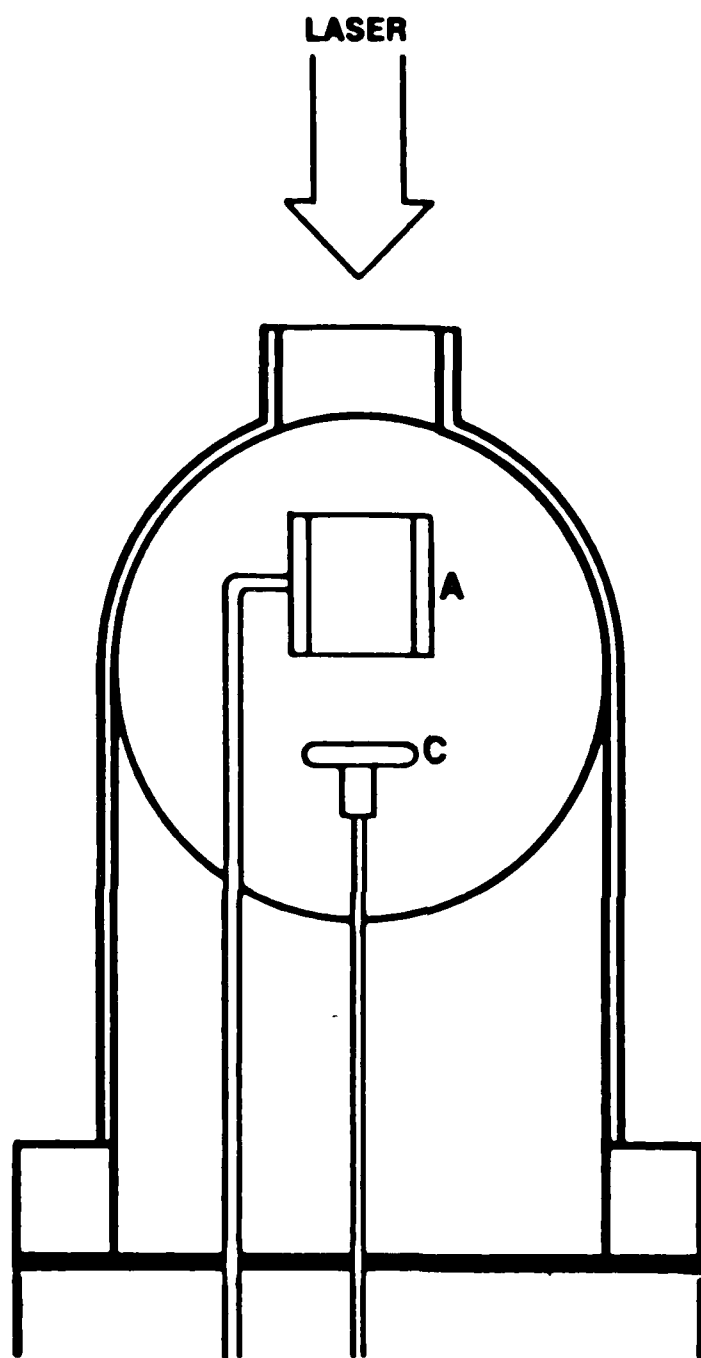
LASER

Figure 1. Diode Configuration for Cesiated Cathode Experiments

an applied potential of 990 V and increasing laser powers
(Figure 2). These oscillograms showed an initial rapidly
rising thermionically generated electron beam followed by the
formation of a plasma. For the multitrace figures, the
different profiles were temporally staggered for easier
visualization. Temporal separation between the thermionic
emission and onset of the plasma decreased with increasing
laser power.

Qualitatively, we interpret the results to show that
laser irradiation of the cesiated surfaces rapidly initiates
thermionic electron emission, with subsequent plasma formation
from desorbed cesium atoms ionized by these electrons. As the
laser power is raised to increase the intensity of the
electron beam, the plasma is formed more quickly after the
onset of irradiation.

The extent of plasma formation can, in fact, be
restricted by limiting the available charge stored in the
charging capacitor. A series of experiments was performed
with lower capacitances of several tens of picofarads
furnished by small lengths of coaxial cable. With the
corresponding charge to the diode also reduced, a series of
temporally shorter electron pulses was recorded, as shown in
Figure 3. At the lower laser powers, the initial current rise
is moderate, consuming a limited amount of the available
charge. Thus, there appears a longer tail, due probably to
the formation of plasma, until a sharp drop in current signals
that the charge has been depleted. As the laser energy
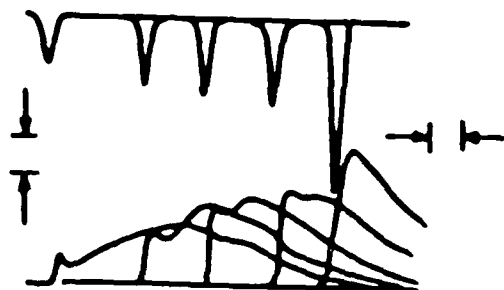
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Figure 2. Profiles of Electron Emission as a Function of Increasing Laser Energy for an Applied Voltage of 900 V (Time Scale: 200 ns/div)
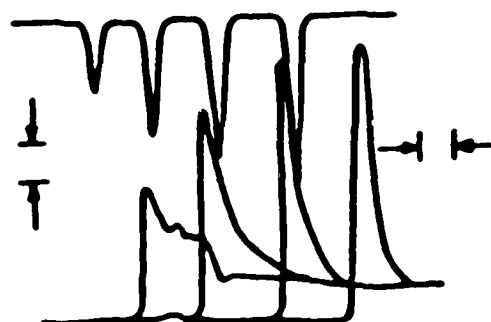
Figure 3.   Electron Emission with a Coaxial Cable pF Capacitor
            (Time Scale: 200 ns/div.   Applied Voltage: 1.5 kV)

increases, so does the intitial rise in current with a reduced pulse duration. The nonzero dc current at the end of the pulse can be virtually eliminated by increasing the value of the capacitance-charging resistor. The current rise appears to saturate at the space-charge-limited value.

Increasing the applied field raises the space-charge-limited current and the charge available to the diode. The two current profiles presented in Figure 4, for applied voltages of 1.5 kV and 2.5 kV, show peaks limited by space-charge effects. As the applied voltage was increased further, the peak currents became emission-limited rather than space-charge limited at the available laser powers. Such charge limitation can be seen at two of the highest applied voltages used in these tests where the peak currents, shown in Figure 5, were below their space-charge-limited values, and were seen to scale with the applied voltage, i.e., with the available charge.

BARIUM-DISPENSER CATHODES

Thermionic dispenser cathodes are composed of a porous refractory marix base impregnated with barium compounds. These emitters are first thermally activated, during which time free barium diffuses to the surface. A combination of barium and barium oxide at the surface provides the low work function needed for significant thermionic emission. B-type cathodes, containing oxides of barium, calcium and aluminum, typically have work functions near 2.05 eV and operate continuously at 1400 K.

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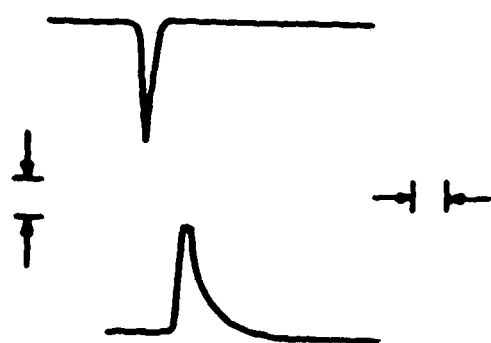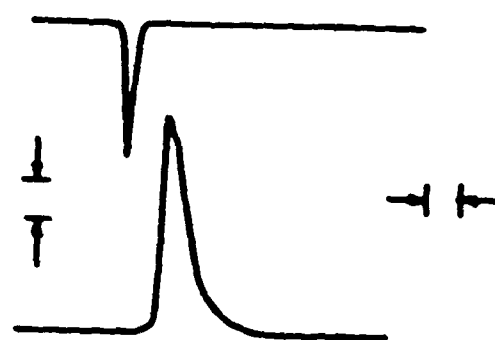
Applied Voltage: 1.5 kV   2.5 kV

Figure 4. Space-Charge-Limited Electron Emission at Two Values of Applied
           Voltage and Low Capacitances in the Picofarad Range
           (Current: 57 mA/div. Time: 200 ns/div)

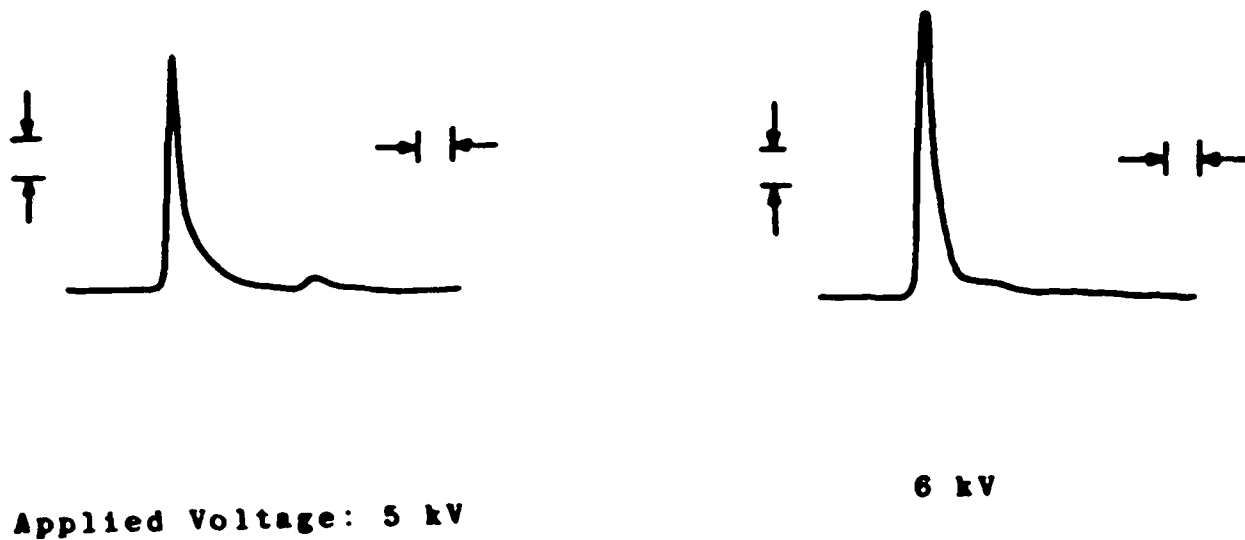11

Applied Voltage: 5 kV

6 kV

Figure 5. Charge-Limited Electron Emission at Two Values of Applied Voltage and Low Capacitances in the Picofarad Range
(Current: 100 mA/div. Time: 200 ns/div)

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The cw-emitted current density from a typical B-type dispenser cathode is shown in Figure 6 as the solid portion of the "dispenser" line with a maximum emission of 10 to 20 A/cm^2 The dashed region of this line represents the extension to higher current densities and temperatures which may be possible by pulse heating the surface with a laser beam.

Pulse heating dispenser cathodes, for example, to 1625 K is, according to Figure 6, sufficient for thermionic emission of a current density of 100 A/cm^2. However, at this temperature, the vapor pressure of free barium is 150 torr, or about an order of magnitude larger than when the cathode is operated at a conventional cw value of 1400 K. Although this increase in pressure would be intolerable under continuous operation, heating the surface for, say, 1 μs at a repetition rate of 100 Hz results in a duty factor of 10^{-4}, with an a average evaporation rate of only 10^{-3} of that sustained at a constant 1400 K.

A pulsed laser can, therefore, be used to heat the surface of the dispenser cathode enough to allow an electron emission density larger than that possible under cw operation. Because the pulse duration is so short, chemical activation of the cathode and proper diffusion of the barium to the surface must be accomplished between the laser pulses. Consequently, the cathode should be continuously heated to a level appropriate to refurbish the surface for the laser pulses. Such background dc heating will also reduce the energy requirements
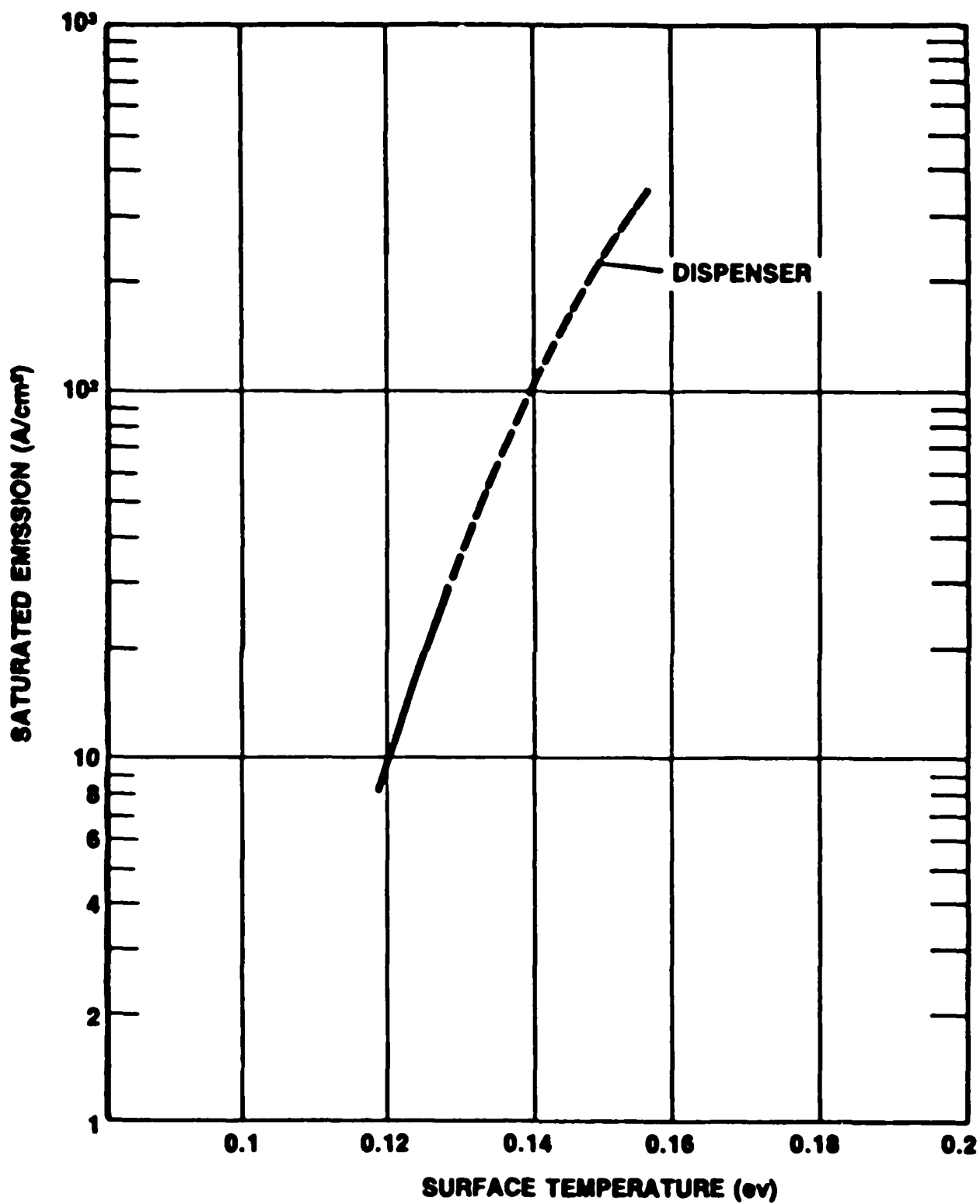
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Figure 6. Electron Emission from a Conventional Dispenser Cathode. The Dashed Portion of the Line Represents the Region Unsuitable for cw Operation

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of the laser, because each pulse only needs to raise the surface temperature several hundred degrees.

In order to evaluate the usefulness of laser-driven dispener cathodes, a series of experiments was performed with the cesium/tungsten diode geometry modified to accommodate a dispenser configuration. Specifically, a planar B-type cathode, 1 cm in diameter, and containing a resistance heating element, replaced the previous tungsten electrode. The cylindrical anode was modified by installing a 30 x 30 molybdenum mesh grid of 2.5 mil-diameter-wire across the opening nearest the cathode. Grid-to-anode interelectrode spacing was reduced to approximately 0.25 cm (Figure 7).

The interelectrode region could be viewed at 90° to the laser beam, through a chamber window. Any visible fluorescence emitted from this region, indicating the formation of a plasma, was spectrally and temporally resolved with a 1/4-m Jarrell-Ash monochromator and an 1P 28 photomultiplier. The Nd:glass laser was operated in a Q-switched mode at the fundamental 1.06 μm wavelength. The laser pulse width was 50 ns (FWHM) with repetition rates limited to about 1/min. Output power could be varied from 5 to 70 MW. The laser signal was monitored by a silicon photocathode. The diode voltage was monitored with a capacitance-dividing probe constructed in-house. All signals were recorded as oscillograms.

The observance of interelectrode fluorescence in a band centered at 600 nm, where strong emission from both BaI and BaII is expected, was considered to be indicative of plasma
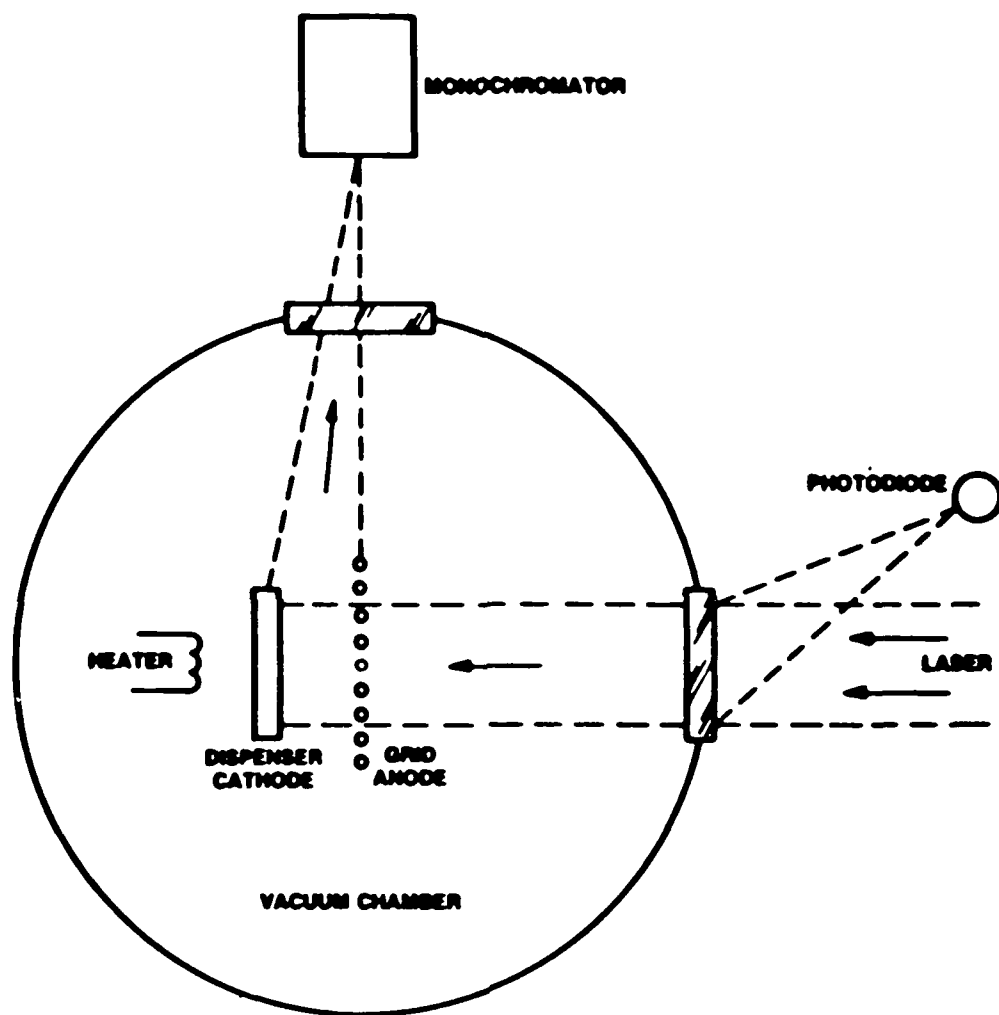
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Figure 7. Experimental Arrangement for Dispenser Cathode Experiments

formation. Temporally resolved traces of this fluorescence and of the diode current showed that the onset of the fluorescence occurred nominally 50 ns after initiation of electron flow (Figure 8). To ensure that successively taken traces of current and fluorescence lined up temporally, the laser signal was sometimes superimposed on these curves. Moreover, this signal was delayed by a constant value on each trace to preclude interference with the data of interest (Figure 9). With the cathode preheated to between 600 and 800 C prior to laser irradiation, a series of experiments was performed in which the applied voltage was raised from approximately 11 kV to 33 kV, and the incident laser energy was 0.5 J, corresponding to a power 10 MW for the 50-ns (FWHM) pulses. The measured currents, 50 ns after their initiation, ranged from about 3 to 40 A. A "best fit" space-charge-limited curve is presented to show that within the accuracy of the measurements it appears that the electron emission is space-charge limited (Figure 10). Such a limit would be expected for pure thermionic emission, i.e., when a plasma has not yet formed, if the laser power is sufficient to generate the required electron flow. From Child's law the active area of the cathode needed to supply these currents is computed to be 0.16 cm^2 (for the 0.25 cm interelectrode spacing), cor-responding to an active cathode diameter of approximately 0.5 cm. Visual inspection of the emitter's surface indicated a somewhat discolored darker central region, corresponding to these dimensions (Figure 11). The thermionic current
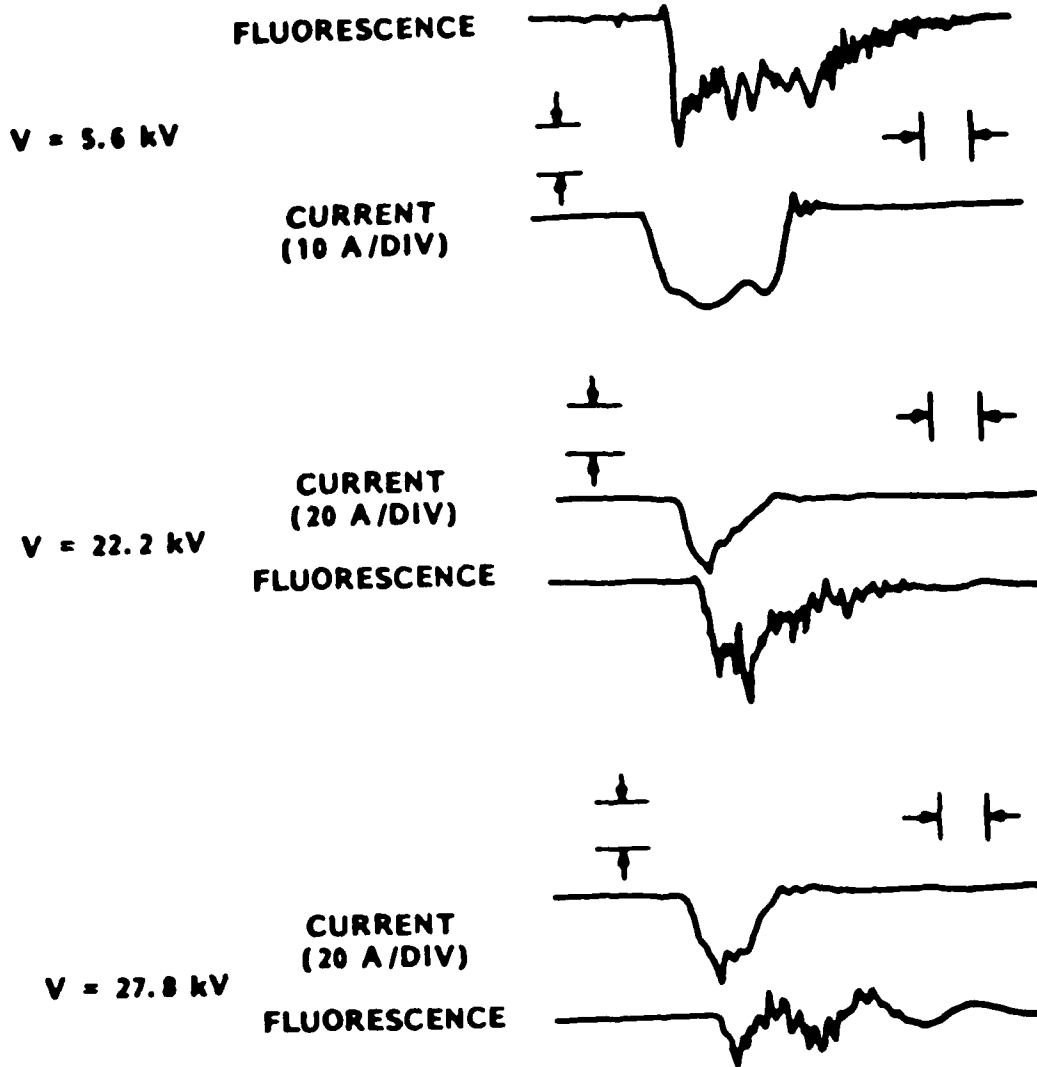
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Figure 8. Diode Current and Fluorescence at 600 nm
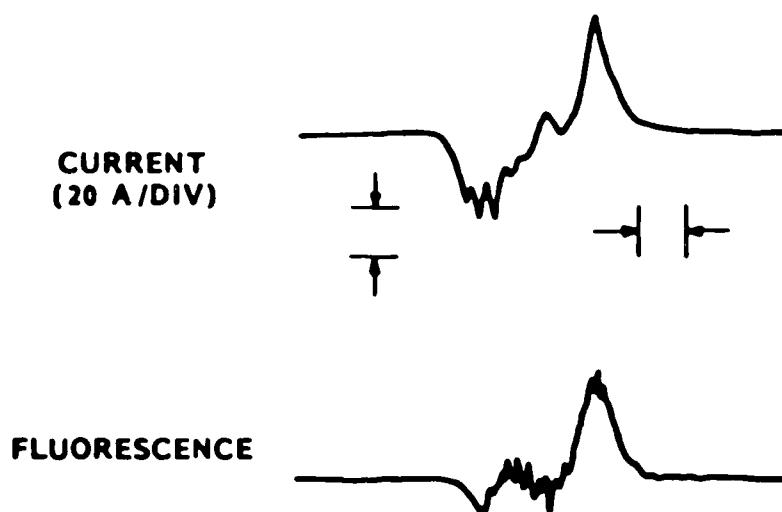(Irradiated Cathode Spot Diameter ∿0.5 cm; 100 ns/DIV)

CURRENT
(20 A/DIV)

FLUORESCENCE

Figure 9. Diode Current and Fluorescence with Delayed Laser Profile
Overlayed (Irradiated Cathode Spot Diameter ∿0.5 cm;
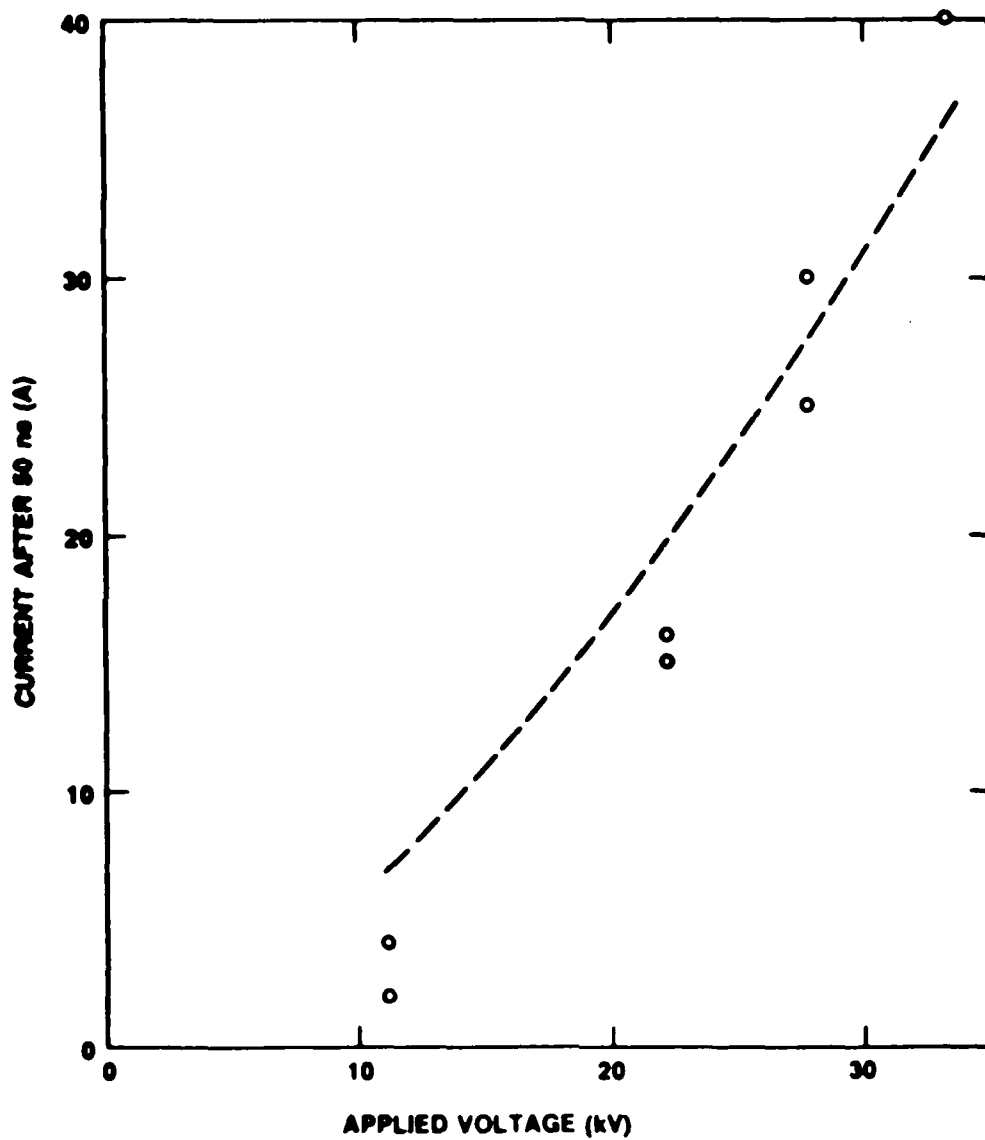V = 27.8 kV; 100 ns/DIV)

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Figure 10. Measured Current After 50 ns of the Beginning of Current Flow as a Function of Applied Voltage (The dotted line represents a best fit space-charge-limited curve)
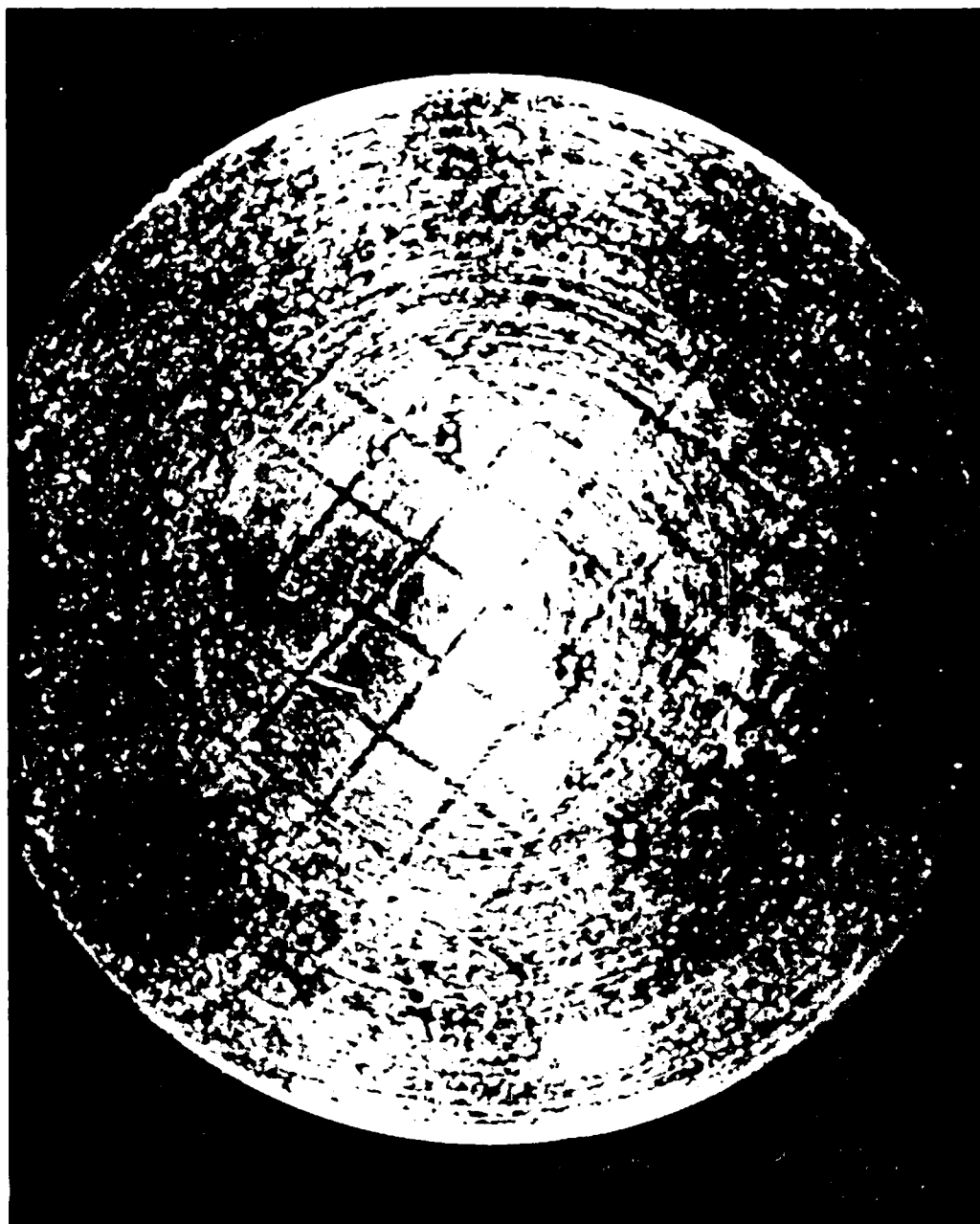
Figure 11.

densities consistent with this area and the observed currents were over 200 A/cm² at the highest applied voltage of 33 kV. Expanding the laser beam with a diverging lens to cover a diameter on the cathode of approximately 0.7 cm, resulted in drawing a current of 75 A at this voltage, which corresponds to a current density of 190 A/cm². Current profiles taken at three different voltages again showed the peak currents to be space-charge limited (Figure 12).

The electron charge in the experiments discussed so far was furnished by a 10-foot-long cable with a capacitance of about 300 pF. Increasing this capacitance by the addition in parallel of up to 500 pF, had no effect on the initial part of the current profiles to their peak values, and produced only minor elongation in the subsequent pulse length. However, when the total capacitance was raised to a value of 2100 pF the formation of a strong plasma was observed. Under these conditions, an initial peak was seen at nominally 50 ns, whose amplitude was twice that observed in the lower capacitance tests. Since the ratio of these initial peaks for different applied voltages obeyed Child's law, it strongly suggested that no plasma is formed during the first 50 ns of the pulse (Figure 13).

In order to further study plasma formation and diode closure, and to estimate the peak temperature of the pulse-laser-irradiated cathode surface, a triode was constructed (Figure 14). In this geometry, the anode and Faraday cup were raised to the same potential, and the experiments were

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V = 22.2 kV

V = 27.8 kV

V = 33.3 kV
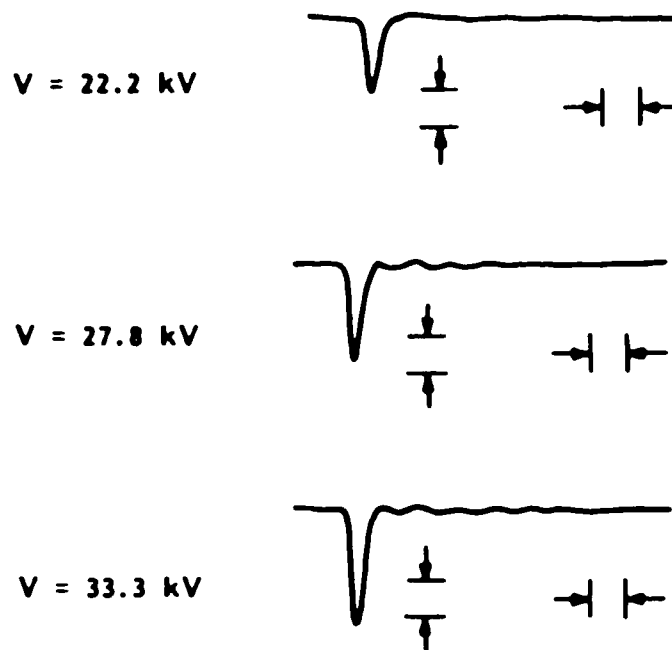
Figure 13. Diode Current at Various Voltages
(Irradiated Cathode Spot Diameter ∿0.7 cm;
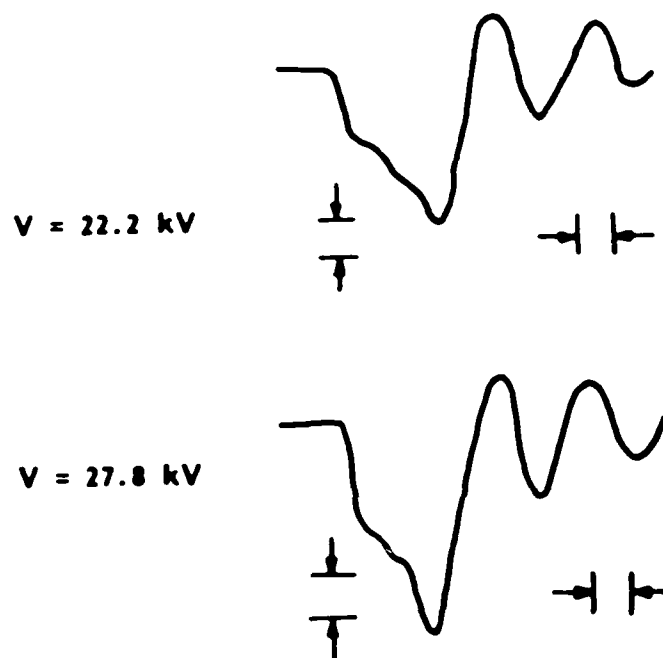25 A/DIV; 100 ns/DIV)

V = 22.2 kV

V = 27.8 kV

Figure 13. **Diode Current with the Charge Supplied by 2100 pF of Capacitance (50 A/DIV; 100 ns/DIV)**
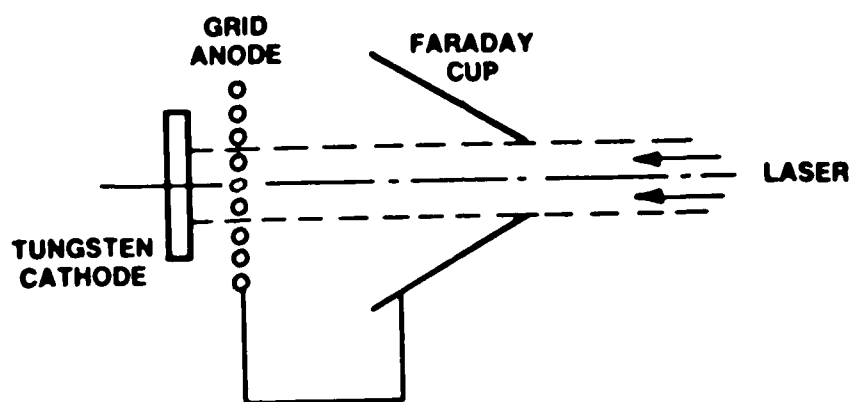
Figure 14. Schematically Represented Triode

simplified by using a bare sintered tungsten cathode with a work function of 4.6 eV. In the first series of tests, a large resistor limited anode currents to milliamperes or less. Simultaneously, currents of several amperes were drawn by the Faraday cup at applied voltages of 5 to 11 kV. As before, the ratios of peak currents (at the Faraday cup) were in agreement with Child's law, thus indicating no appreciable formation of an interelectrode plasma during at least the first part of the pulse. Since only about 10 percent of the stored charge was consumed in the entire pulse, significant palsma formation at any time in the pulse is doubtful. The incident radiative energy ranged between 2.25 and 2.75 J/cm^2. For the approximate 8-mm diameter (0.5 cm^2) cathode surface irradiated, and the expected 50 percent absorption by tungsten at the 1.06 μm wavelength, the surface will reach a maximum temperature near its melting point. At 3000 K, for example, Richardson's equation predicts an emission of 20 A/cm^2. The measured space-charge-limited currents of up to 8 A (16 A/cm^2) are, therefore, within the range expected.

When the impedance in the anode circuit was reduced to 100 Ω or less, significant current signals were observed from both the anode and Faraday cup. During the anode signal's initial rise of approximately 25 ns, the Faraday cup signal also rose indicating that any plasma front which may have formed had not yet closed across the interelectrode region. At the end of this period, the anode signal showed a first peak indicated by a well-defined bump, after which it con-

tinued to rise. During this continuing rise, the Faraday cup signal fell, suggesting that the cathode-anode gap was filled with plasma (Figure 15). The observed bump had also been seen in the previous dispenser cathode experiments, where it was thought to signal the beginning of a plasma. These triode tests confirmed that suspicion.

The influence of varying the charge available to the cathode-anode circuit is shown in Figure 16. For the results presented in the figure, the anode and Faraday cup had different amounts of charge available to them. (They were connectd to different capacitors). The Faraday cup was coupled to the cathode by a constant capacitance of 500 pF. Both electrodes were charged to the same potential. The upper traces show the Faraday cup and anode currents with 17 pF available to the anode, whereas the lower traces present these curves for 50 pF. The Faraday cup signals during the first 50 to 100 ns are reasonably similar in both sets of traces, suggesting that this region is dominated by thermionic electrons. Subsequently, however, as a plasma forms, the low capacitance of the upper cathode-anode circuit restricts the electron flow to this electrode, thus forcing the plasma electrons to appear at the Faraday cup. In the lower traces, the larger capacitance of the anode circuit allows some of the plasma electrons to flow to this electrode with a corresponding decrease in the current to the Faraday cup. Eventually, no more charge can be collected by the anode, and the remaining plasma electrons flow to the Faraday cup.
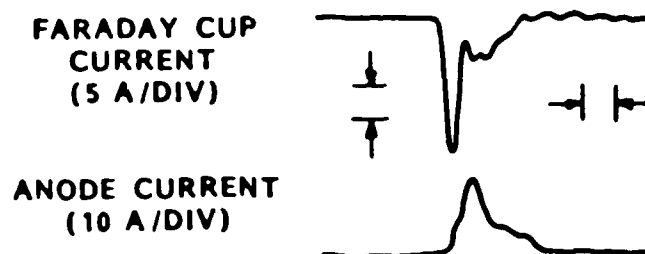
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FARADAY CUP
CURRENT
(5 A/DIV)

ANODE CURRENT
(10 A/DIV)

Figure 1. Faraday Cup Currents
(50 ns/DIV; V = 24 kV; $C_{Anode} = C_{FC} = 50$ pF)

FARADAY CUP
CURRENT
(20 A/DIV)

ANODE CURRENT
(10 A/DIV)

C_A = 17 pF

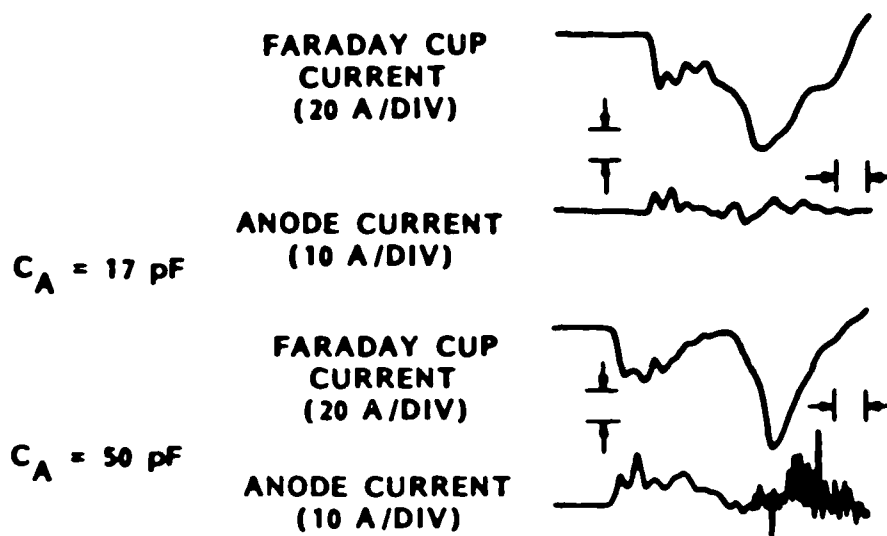FARADAY CUP
CURRENT
(20 A/DIV)

C_A = 50 pF

ANODE CURRENT
(10 A/DIV)

Figure ... Faraday Cup and Anode Currents with a Faraday Cup
Capacitance of 500 pF and Different Anode Capacitances
(V = 24 kV; 50 ns/DIV)

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When a single capacitor was used to supply the charge to both the anode and Faraday cup, a longer (apparently thermionic) region, lasting approximately 150 ns, was observed (Figure 17). Subsequent plasma formation was seen in the decreased Faraday cup signal and the, concurrently, increasing anode current.
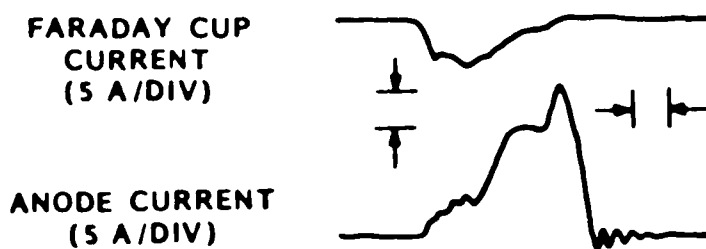
FARADAY CUP
CURRENT
(5 A/DIV)

ANODE CURRENT
(5 A/DIV)

Figure 17. Faraday Cup and Anode Currents with the Same
Capacitance Supplying Charge to Both of these Electrodes
(V = 11 kV; 100 ns/DIV)

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CONCLUSION

Overall, the results from these experiments indicate that both cesium-coated tungsten surfaces and dispenser cathodes will thermionically emit electrons when rapidly heated by a laser pulse. The process, at least for cesium, is a nonequilibrium one in that the peak surface temperture is far in excess of that which allows the cesium coverage needed to explain the observed currents under equilibrium conditions. The thermionic currents were always seen to rise rapidly to their peak value. In many cases, subsequent formation of a plasma was evident. For large microfarad capacitance, this plasma greatly elongated the pulse. Reducing the capacitance to small values in the picofarad range decreased pulse widths by limiting the charge.

A rapidly rising Q-switched laser pulse irradiating a thermionic dispenser cathode generated a short, intense electron pulse whose initial region is dominated by thermionic processes. Peak thermionic current densities over 200 A/cm^2 were observed in this study. These currents were limited by the applied voltage in the experiments which ranged up to 33 kV. Maximum currents of 75 A were recorded. Measurements of the fluorescent radiation at 600 nm, emitted from the diode's interelectrode region, were used as an indicator of plasma formation. This fluorescence showed a delay of nominally 50 ns with respect to the beginning of the current pulse. The delay varied somewhat depending on the magnitude of the

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current drawn. Further evidence for an initial thermionic-dominated region was provided by the data from the triode tests. Although a pure tungsten cathode was used in this geometry, the current profiles were similar to those obtained with the dispenser cathode. Comparison of the time-resolved Faraday cup and anode currents showed an initial Faraday cup signal corresponding to the thermionic region. The subsequent formation of a plasma caused the expected decrease in the Faraday cup current. The peak currents drawn from the tungsten cathode verified that the cathode surface was heated by the strong laser pulses to maximum temperatures near the material's melting point.

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